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A CRITIQUE OF AIRCRAFT AIRFRAME COST MODELS.(U)

SEP 77 J P LARGE, K M GILLESPIE F49620-77-C-0023

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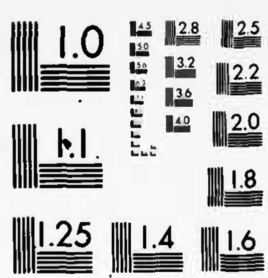

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September 1977
R-2194-AF

A Critique of Aircraft Airframe Cost Models

J. P. Large, Capt. K.M.S. Gillespie

A Project AIR FORCE report
prepared for the
United States Air Force

Rand
SANTA MONICA, CA. 90406

PREFACE

The Rand Corporation published three aircraft airframe cost models in the period 1966 through 1976. During that decade other organizations approached the same task with somewhat different procedures. With such a variety of models to choose from, the question arises, which of them is the most useful? The Cost Analysis Division, Directorate of Management Analysis, Headquarters United States Air Force, asked Rand to review several of the models to determine their relative merits and limitations. The work was undertaken as part of the Analytical Methodology Research project under Project AIR FORCE (formerly Project RAND). It should be of interest to persons in the Air Staff and elsewhere in the Department of Defense who rely on parametric models for estimating or validating airframe costs.

This report is a companion to J. A. Dryden and J. P. Large, *A Critique of Spacecraft Cost Models*, R-2196-AF (forthcoming). While the report was being prepared, coauthor Captain K. M. S. Gillespie was on duty at The Rand Corporation in the Management Sciences Department. At present he is with the Office of the Comptroller, Headquarters Air Force Systems Command.

SUMMARY

Parametric cost models are widely used throughout the Department of Defense for purposes ranging from advanced system studies to proposal evaluation. In system studies where a number of alternative ways of achieving a specific objective are to be evaluated, a cost model provides consistent, comparable estimates and does so quickly and cheaply. The emphasis there is on *relative* accuracy. Use of a cost model in preliminary evaluation of a contractor's proposal implies a faith in the *absolute* accuracy of the output, a faith that may not be justified. Such models may provide better estimates than those generated by a contractor, because the estimates reflect industry-wide experience and contain a built-in allowance for the unforeseen costs of all kinds that occur in a typical program. However, cost models are not infallible, and the user must be aware of the limitations of whatever model he is using.

This report examines a sample of seven aircraft airframe cost models: three Rand models published sequentially from 1966 to 1976; one developed by Planning Research Corporation in 1965 and revised in 1967; two from J. Watson Noah Associates (1973 and 1977); and a transport aircraft model from Science Applications, Inc. (1977). The intent is to determine whether the model output is reasonable over a broad range of inputs, what limitations should be noted, and where one model might be preferable to the others.

Of the three Rand models, we believe the most recent one is best suited for current estimating problems, primarily because its data base is better and includes more contemporary aircraft. The data sample in the PRC model is composed of aircraft developed in the 1950s and earlier; the model tends to underestimate the cost of small aircraft and overestimate large ones. The second Noah model is an improvement over the first and generally does a good job provided the user is able to specify whether a new airplane will require "significantly new and complex technology." The user's judgment on that issue determines whether the estimate will be good or bad. The Science Applications, Inc.

model appears to be reliable for estimating the production cost of transports in the speed regime of the aircraft in its data sample.

Our examination shows that all the models have some deficiencies and all should be used with caution. The more recent models appear to be better than the older ones, which may be taken as a sign of progress, but it is plain that more progress is needed. Some of the lessons learned in this review may be helpful in pointing out how the next generation of aircraft airframe cost models could be improved.

ACKNOWLEDGMENTS

We wish to acknowledge the helpful comments provided by M. N. Beltramo of Science Applications, Inc.; R. F. Burnes of PRC Systems Services Co.; and J. W. Noah of J. Watson Noah Associates on the chapters discussing airframe cost models developed by their several companies. We are also indebted to K. E. Marks and J. R. Nelson of Rand for careful technical reviews of an earlier draft of this report. All errors of omission or commission remain, of course, our responsibility.

CONTENTS

FIGURES

TABLES

I. INTRODUCTION

The Rand Corporation has been developing parametric methods of estimating aircraft airframe costs for many years, initially for use within Rand but more recently for use in planning and evaluation studies by various DoD organizations as well. The Rand airframe models[1-4] are not the only ones available to such organizations. Planning Research Corporation developed a model for OSD in 1967 that is still in use;[5] J. Watson Noah Associates developed one for OPNAV-96[6] that has recently been revised;[7] and Science Applications, Inc., has produced a transport aircraft model for the National Aeronautics and Space Administration.[8] Most major airframe companies have their own models, but they may run other models as well to compare their own estimates with those based on a larger, less selective sample.

Parametric cost models of the type discussed here are designed to be used at a time when very little is known about the aircraft. Experience teaches that early optimism about aircraft costs is rarely warranted. The goal is to generate estimates that include the cost of the program delays, engineering changes, data requirements, and inefficiencies of all kinds that occur in a normal program. It is implicitly assumed that every program will have its fair share of problems, that all contractors are equally productive, and that all development and production strategies are equally efficient. By design, cost models of this type are, like justice, blind--they treat all programs alike. When properly constructed, they can provide useful planning estimates. They cannot be depended upon to predict actual program costs.

There are a number of differences in the models mentioned above, and comparisons among them are not completely fair because they are intended to serve different purposes. That fact is often overlooked by users who are concerned simply to find out which model yields the best estimate. The best estimate in some cases is the estimate that can be obtained the soonest or can be obtained with the least information about a proposed airplane. In other cases the best estimate is one that allows an engineer to study the cost implications of design changes, and only a very detailed model provides that capability. To obtain relative accuracy at that level, however, often means sacrificing absolute accuracy at the total-aircraft level; the whole does not always equal the sum of the parts.

In principle, then, comparisons among models should take into account their intrinsic differences--different inputs, outputs, levels of detail, intended uses, etc.--but in practice comparisons generally focus on the bottom line. And despite cautionary notices such as "this model is intended primarily for use in long-range planning, not for evaluating contractor proposals," the models are often used in preliminary evaluations of cost proposals. Consequently, it seemed worthwhile to examine some of the aircraft models available in the open literature.* In general, the models themselves are not reproduced here because of their length. The only exception is in the case of the JWN models, which consist of two equations, one for nonrecurring cost and one for recurring.

The Rand and PRC models are examined at more length than the other two because they estimate at the cost-element level. The JWN models estimate total costs only, while the SAI model provides total-cost estimates at the subsystem level. In the course of the examination, consideration is given to the functional forms, independent variables, and data samples. First, we look for anomalies, unexpected and unfortunate curve shapes that limit the range of a model. For example, a model may give good estimates for aircraft of a given weight and speed but bad estimates for aircraft in a different weight range or speed regime. Second, estimates from the models are compared with actual costs for nine aircraft. The term "actual" is somewhat inaccurate for three reasons. In some cases costs are projections from the number produced--e.g., an "actual" is inferred for 100 C-5As from the cost of the 81 produced. In addition, all dollar costs were escalated to 1975 dollars, and that introduces an element of error.† Finally, manhours were

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*Although they are referred to as *airframe* models, they actually include all program management and system engineering performed by the prime contractor including that required to integrate the engines and avionics into the airframe.

†The procedure used is that described in H. G. Campbell, *Aerospace Price Indexes*, The Rand Corporation, R-568-PR, December 1970.

converted to dollars using the same composite rates for all contractors. Thus, differences in actual cost due to differences in wage and burden rates were eliminated.

The intent of our examination is to determine whether the output of the various models is reasonable over a broad range of inputs; what limitations should be noted; where one model might be preferable to another; and, perhaps most important, how the next generation of models can profit from experience gained to date.

II. DAPCA*

The first Rand report to treat airframe cost-estimating in a comprehensive way was published in 1966. It established a pattern that has not varied greatly with subsequent reports. Only the airframe portion of total aircraft cost is included, but that includes system engineering, program management, flight test, etc. Individual cost elements are treated separately. Estimates are made in hours rather than dollars, wherever possible, and independent variables are limited to those that are both statistically significant, reasonable in a causal sense, and available at a time when specific design and program information is uncertain. Variables involving time were used sparingly because of their unreliability. In a preliminary design study, an estimate of date of first flight or first production aircraft was felt to be too uncertain. Similarly, the length of a development or production program is unlikely to be estimated accurately. Subjective factors, such as degree of technological advance, were also ruled out, because *a priori* judgments often differ from *ex post facto* judgments. Thus, by design, the models essentially deal with averages. As it develops, the models are sometimes used for programs well into the development cycle, and at that point the argument against time-related variables is less persuasive.

The principal differences among DAPCAs I, II, and III have been the data sample and the quality of the data. By the time DAPCA III was produced, the authors were able to benefit from the considerable effort at data collection that preceded their work and to validate the data with the cooperation of airframe contractors. Changes in the sample were based primarily on concern that development and production experience on older aircraft may not be relevant today and on the opportunity to add contemporary aircraft to the sample. As shown by Table 1,

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*DAPCA is an acronym for Development and Procurement Costs of Aircraft, and, strictly speaking, it refers to a series of three computer models. We use the term here as a convenient way to refer to the three generations of airframe models that later were incorporated into DAPCAs I, II, and III.

converted to dollars using the same composite rates for all contractors. Thus, differences in actual cost due to differences in wage and burden rates were eliminated.

The intent of our examination is to determine whether the output of the various models is reasonable over a broad range of inputs; what limitations should be noted; where one model might be preferable to another; and, perhaps most important, how the next generation of models can profit from experience gained to date.

Table 1

DAPCA DATA SAMPLES

	I	II	III
	A-3	A-3	A-3
	A-4	A-4	A-4
	A-5	A-5	A-5
	B-36	A-7	A-6
	B-47	B-47	A-7
	B-52	B-52	B-52
	B-57	B-58	B-58
	B-58	RB/B-66	RB-66
	RB/B-66	C-124	C-5
	C-124	C-130	C-130
	C-130	C-133	C-133
	C-133	KC-135	KC-135
	KC-135	C-141	C-141
	F-3	F-3	F-3
	F-4	F-4	F-4
	F-8U	F-84	F-6
	F-84	F-84F	F-14
	F-84F	F-86	F-100
	F-86	F-86D	F-102
	F-86D	F-89	F-104
	F-89	F-100	F-105
	F-100	RF-101	F-106
	RF-101	F-102	F-111
	F-102	F-104	T-38
	F-104	F-105	T-39
	F-105	F-106	
	F-106	F-111	
	T-37	OV-10	
	T-38	T-38	
	29	29	25
Range of:			
Airframe unit weight (lb)	2546-112,500	5072-112,500	5072-279,145
Maximum speed (kn)	274-1220	274-1262	309-1370
First flight dates	1947-1959	1947-1967	1953-1970

DAPCA II dropped the B-36, B-57, F-8U, and T-37 from the sample and added the A-7, C-141, F-111, and OV-10. DAPCA III dropped all aircraft with first flight dates before 1952, the OV-10 (because of its low performance), and RF-101 (because F-101 and RF-101 costs could not be separated with confidence), and added the A-6, C-5, F-6, F-14, and T-39.

As we shall see, for some cost elements the changes had very little effect, but for others--in particular, manufacturing materials--the effect was perceptible. In a few cases the data base was more complete for one cost element than for another; e.g., manufacturing hours were available for all aircraft, but development support costs were missing on several. All available data points were used except, as will be explained later, in the case of the DAPCA III engineering equation.

As described below, the models estimate the major cost elements separately, so users can identify engineering, tooling, and manufacturing-hour requirements. An all-inclusive hourly rate is used to convert hours into dollars. The user is encouraged to enter rates appropriate to a particular company or region if they are known. The 1975 rates used for estimates presented here are:

	Development	Production
Engineering	$26.50	$21.75
Tooling	24.25	22.75
Manufacturing	23.75	22.00
Quality control	24.50	23.00

ENGINEERING

In DAPCA I, total engineering hours are separated into nonrecurring and recurring hours by means of a graphical construct. DAPCAs II and III found that, historically, the definitions of nonrecurring and recurring engineering hours were too inconsistent to allow them to be analyzed statistically as separate cost elements. Those models estimate total engineering hours only. The independent variables in each model are generally the same: airframe unit weight and speed.* DAPCA I offers the option of using thrust in lieu of weight. As shown by Fig. 1, engineering hours increase on a log-linear curve as weight increases; that

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*Airframe unit weight, often called AMPR weight, is defined as empty weight minus the following: wheels, brakes, tires, and tubes; engines--main and auxiliary; rubber or nylon fuel cells; starters--main and auxiliary; propellers; auxiliary power-plant unit; instruments; batteries and electrical power supply and conversion; avionics group; turrets and power-operated mounts; air conditioning, anti-icing, and pressurization units and fluids; cameras and optical viewfinders; trapped fuel and oil.

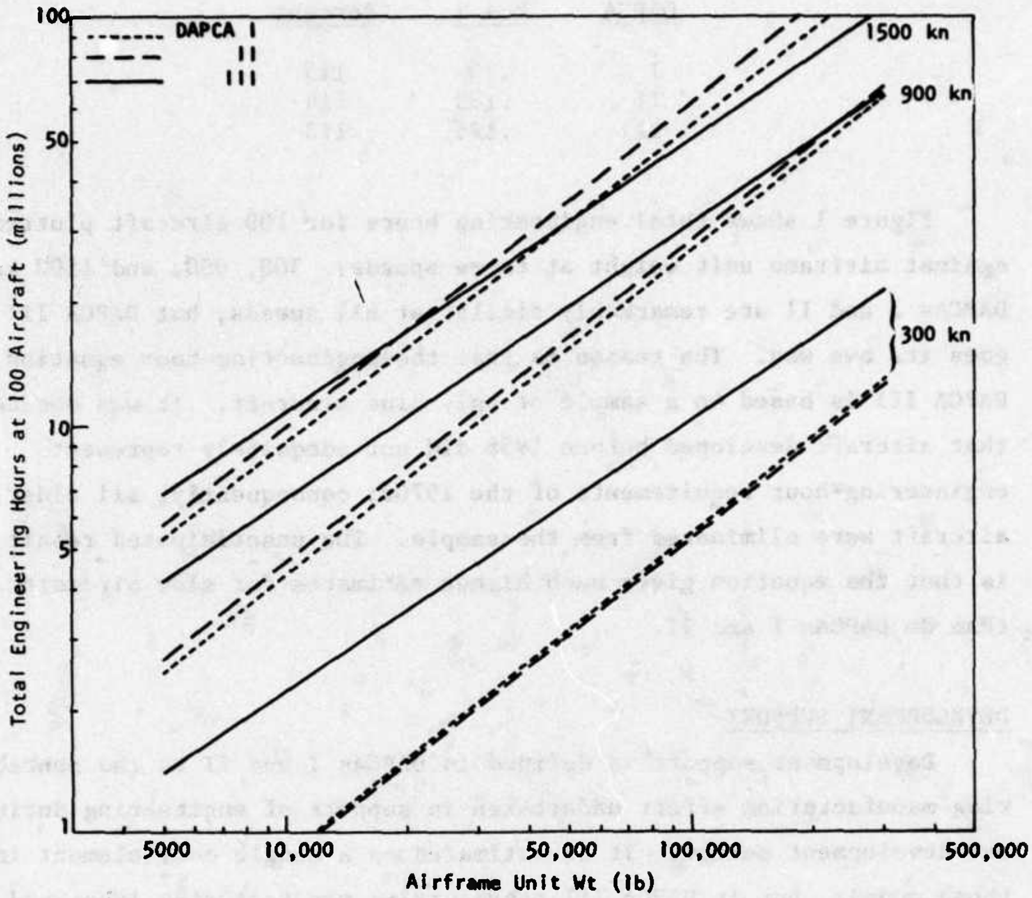

Fig. 1--Comparison of DAPCA engineering-hour estimates at 100 aircraft

will be true of all the Rand curves shown here, because the functional form of the estimating equations in DAPCA for all cost elements except quality control is:

$$Y = aW^b X^c Z^d .$$

A cumulative total learning curve is assumed in each case. The mean slopes in the three models are given below, but the user can enter any value desired.

DAPCA	b + 1	Percent
I	.20	115
II	.183	114
III	.176	113

Figure 1 shows total engineering hours for 100 aircraft plotted against airframe unit weight at three speeds: 300, 900, and 1500 kn. DAPCAs I and II are remarkably similar at all speeds, but DAPCA III goes its own way. The reason is that the engineering-hour equation in DAPCA III is based on a sample of only nine aircraft. It was decided that aircraft developed before 1958 did not adequately represent engineering-hour requirements of the 1970s; consequently, all older aircraft were eliminated from the sample. The unanticipated result is that the equation gives much higher estimates for slow aircraft than do DAPCAs I and II.

DEVELOPMENT SUPPORT

Development support is defined in DAPCAs I and II as the nonrecurring manufacturing effort undertaken in support of engineering during the development period. It is estimated as a single cost element in those models, but in DAPCA III nonrecurring manufacturing labor and materials are estimated separately. Estimating procedures differ more on this cost element than on any of the others.

DAPCA	Independent Variables	Unit of Measurement
I	Initial engineering hours	Hours
II	Airframe weight, speed, number of flight test aircraft	Dollars
III	Airframe weight, speed	Hours (labor) Dollars (materials)

Figure 2 shows that DAPCA I estimates are higher than II and III at all weights and all speeds, whereas DAPCA II is lowest most of the time. The DAPCA II estimate is sensitive to the number of flight test aircraft, however, so it could be higher or lower as that number varies. The slope of the DAPCA II curves is such that cost is almost directly

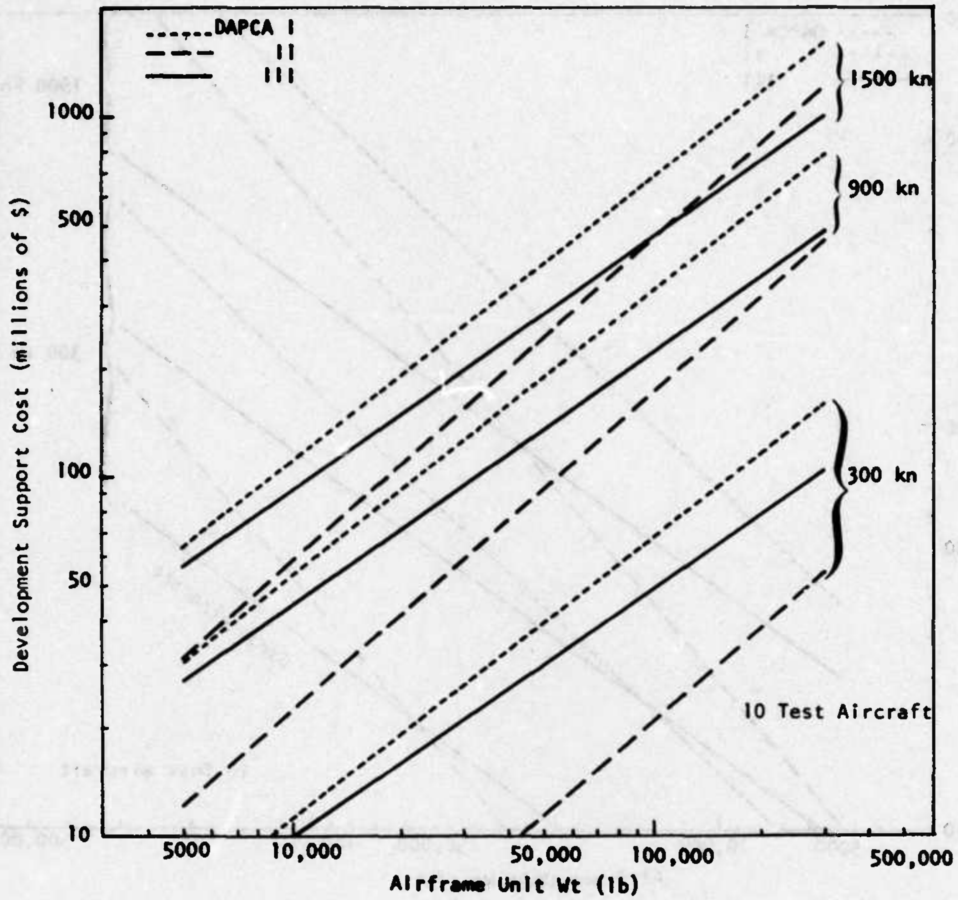

Fig. 2--Comparison of DAPCA development-support estimates

proportional to weight, and that probably results in an understatement of cost at the low end of the scale.

FLIGHT TEST

All three models estimate the cost of flight test operations as a function of speed, weight (for DAPCA I, thrust is an alternative to weight), and the number of flight test aircraft (10 in the Fig. 3 comparison). DAPCA III has in addition a dummy variable to distinguish cargo aircraft from other military types. The varying levels and slopes of curves in Fig. 3 illustrate the diverse results that are possible despite the use of the same independent variables and much of the same basic data.

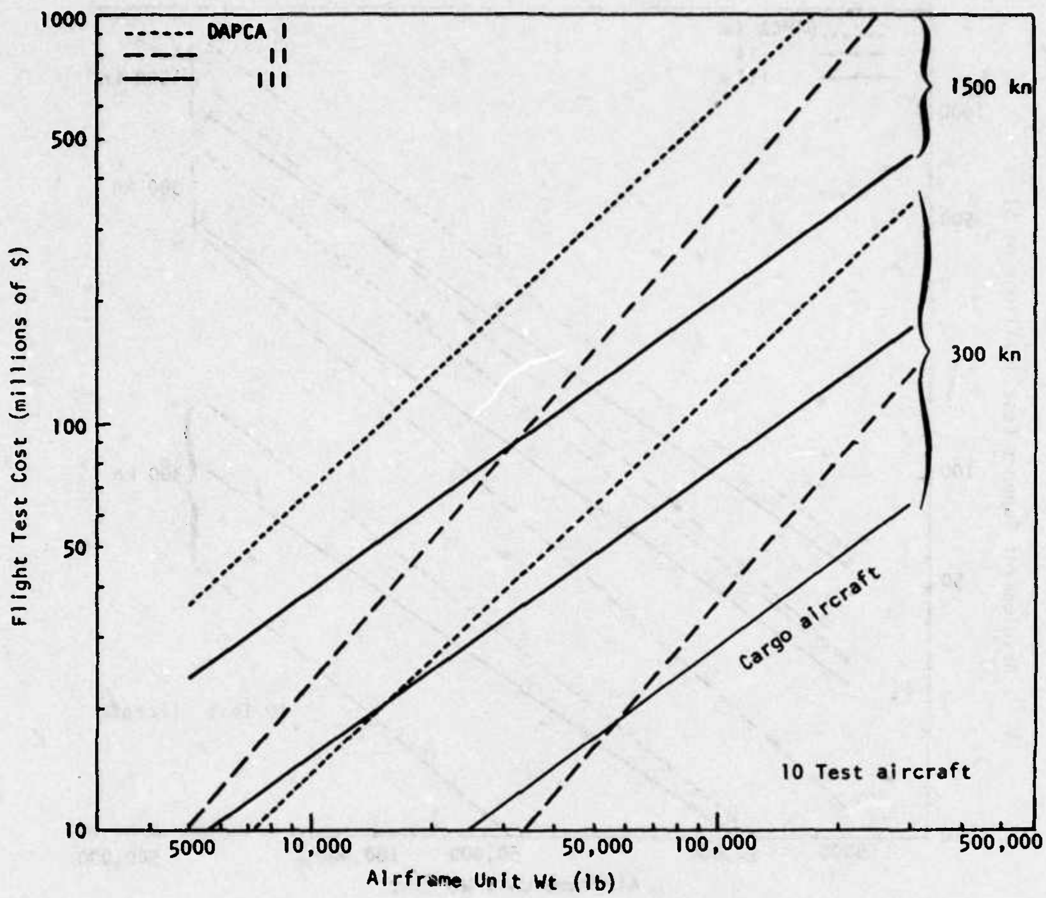

Fig. 3--Comparison of DAPCA flight test cost estimates

The relative positions of these curves are quite sensitive to the number of flight test vehicles chosen, because in each case that number has a different exponent:

$$\text{DAPCA I} \quad N^{1.32}$$

$$\text{DAPCA II} \quad N^{1.281}$$

$$\text{DAPCA III} \quad N^{.72}$$

As shown by Fig. 4, DAPCA III estimates flight test cost for a 30,000-lb, 600-kn airframe to be much higher than the two preceding models when only a few test aircraft are specified. At 20 test aircraft, the

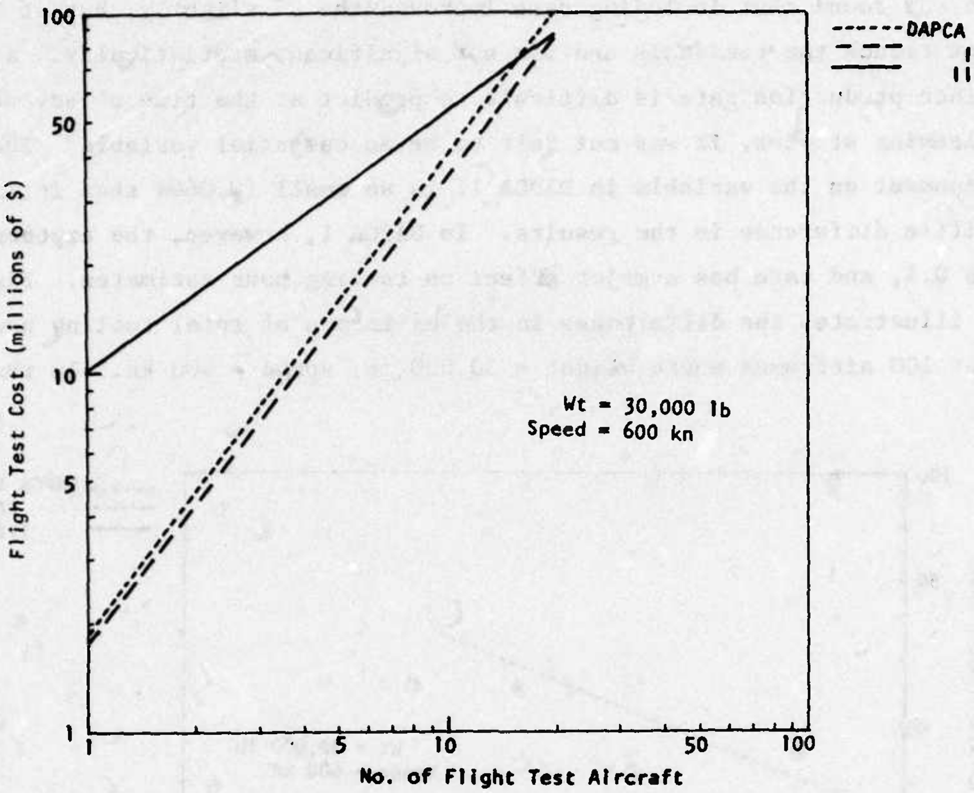

Fig. 4--Number of flight test aircraft vs cost

relative values of the estimates have changed substantially. The fact that the DAPCA I and II exponents are so alike gives them greater credibility; but an exponent greater than 1.0 appears improbable because cost per unit should not increase as the number of units increases. A more thorough study of flight test costs would be necessary to determine which of the models yields the most reliable estimates.

TOOLING

DAPCA I used an empirical procedure to distinguish between tooling provision (nonrecurring) hours and sustaining (recurring) tooling hours; DAPCAs II and III made no such distinction, arguing that definitional inconsistencies among contractors made the distinction meaningless. All three models have airframe unit weight and speed as independent variables. Only DAPCA III does not include a production rate variable. In that model it was found that including rate improved the R^2 slightly, but it did not reduce the residuals and was not significant statistically. Also, since production rate is difficult to predict at the time of advanced planning studies, it was not felt to be an essential variable. The exponent on the variable in DAPCA II is so small (0.066) that it makes little difference in the results. In DAPCA I, however, the exponent is 0.4, and rate has a major effect on tooling hour estimates. Figure 5 illustrates the differences in the estimates of total tooling hours for 100 airframes where weight = 30,000 lb, speed = 600 kn. In that

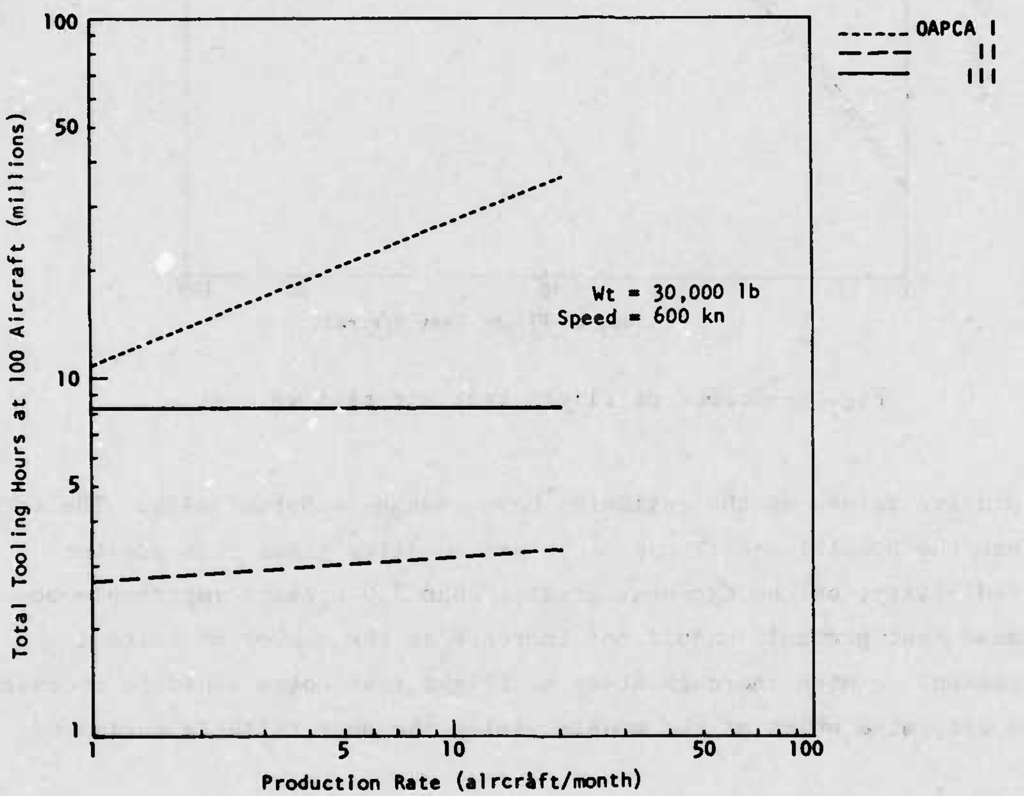

Fig. 5--The influence of production rate on DAPCA tooling-hour estimates

figure the DAPCA I estimate is highest and DAPCA II lowest, but at different weights and speeds relative positions change greatly.

Figure 6 shows how tooling-hour estimates vary as a function of weight at two different speeds. With the benefit of the C-5 data,

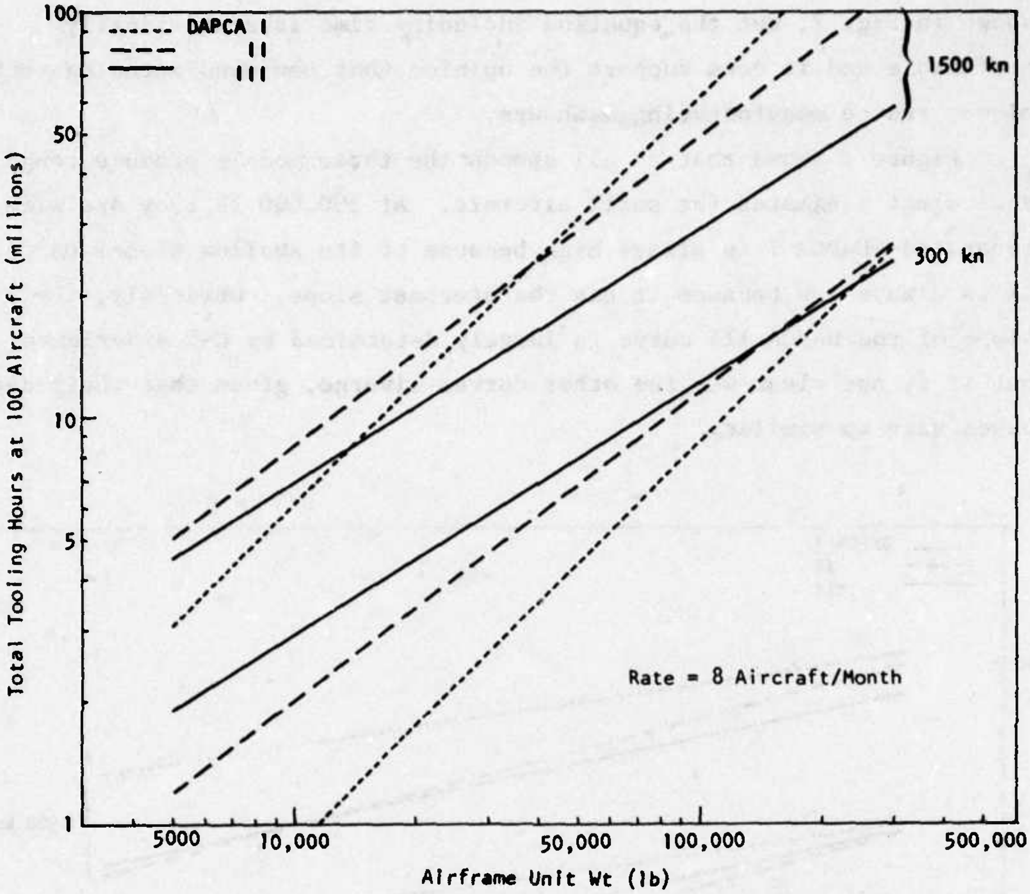

Fig. 6--Comparison of DAPCA tooling-hour estimates

DAPCA III curves reflect the economies of scale more than the others do. Also, DAPCA III is less sensitive to changes in speed than the others. Since it has a higher percentage of supersonic aircraft in its data base, we are inclined to think its speed variable is more realistic.

MANUFACTURING LABOR

Of all the cost elements, manufacturing labor is the one on which the three models agree best. All use the same independent variables--airframe weight and speed--except that DAPCA III offers the option of a third variable, time of flight of first production aircraft, if that information is available. That variable was not used in the comparison shown in Fig. 7, but the equation including time is statistically preferable and it does support the opinion that new manufacturing techniques reduce manufacturing manhours.

Figure 7 shows that at all speeds the three models produce roughly equivalent estimates for small aircraft. At 300,000 lb they are widely separated--DAPCA I is always high because of its shallow slope; DAPCA II is always low because it has the steepest slope. Obviously, the slope of the DAPCA III curve is largely determined by C-5 experience; but it is not clear why the other curves diverge, given that their data bases were so similar.

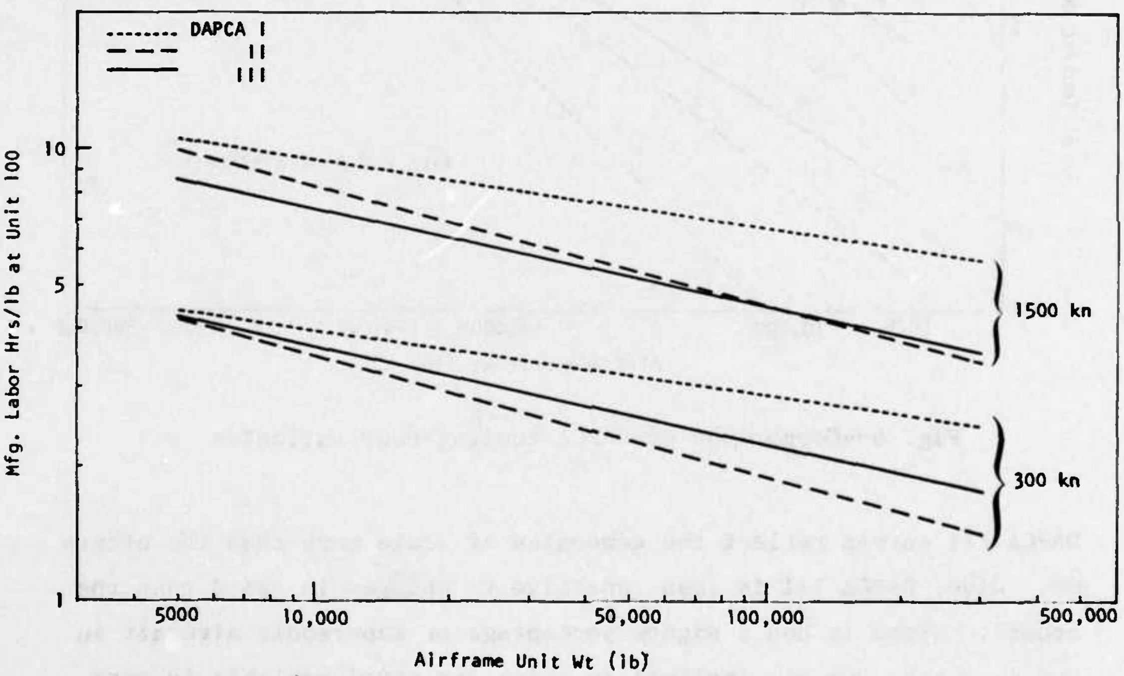

Fig. 7--Comparison of DAPCA manufacturing-labor-hours-per-pound estimates

QUALITY CONTROL

Quality control hours are estimated as a percentage of manufacturing labor hours in each case. DAPCAs I and II use a single factor; DAPCA III distinguishes between cargo aircraft and other types:

DAPCA	Factor
I	.14
II	.13
III	Cargo = .085
	Other = .12

MANUFACTURING MATERIAL

As in the case of manufacturing labor hours, material is estimated as a function of weight and speed with a time variable available as an option in DAPCA III. Use of that variable indicates an increase in material cost over time. Figure 8 shows that DAPCAs I and III agree fairly well on slope but are far apart on level of cost. DAPCA II has a much steeper slope, implying much greater economies of scale. Material cost has always been a problem to identify, because the cost of

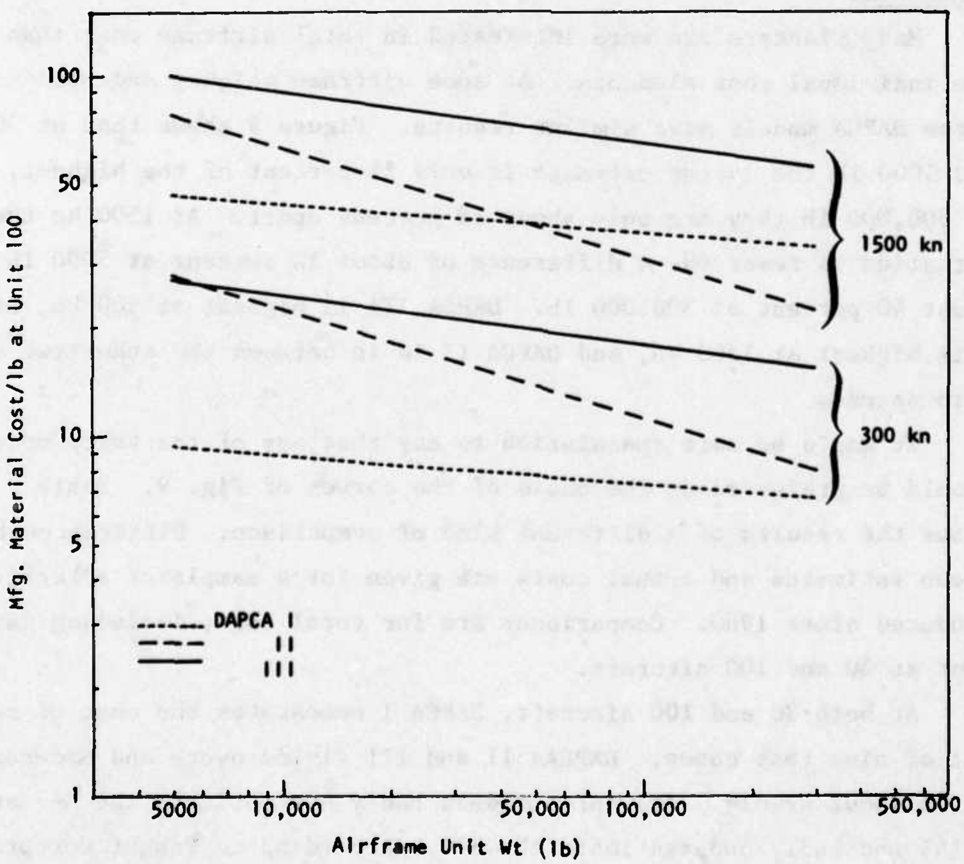

Fig. 8--Comparison of DAPCA manufacturing-material-cost-per-pound estimates

government-furnished aircraft equipment (GFAE) is not included in contractor records and has to be sought out separately. That cost was largely ignored in DAPCA I, and in DAPCA II an arbitrary $100,000 (in current dollars) was added to the cost of each airframe. In DAPCA III, GFAE costs were identified for a number of aircraft in the sample, and an estimating relationship was developed from that data to estimate GFAE costs for the remaining aircraft.

A second factor contributing to the higher level of the DAPCA III curve is simply that apart from inflation, material cost has increased because of a change in materials--e.g., greater use of titanium. The deletion of pre-1952 aircraft from the sample along with the addition of more recent aircraft should give an estimate more in keeping with today's costs.

TOTAL COST

Many planners are more interested in total airframe cost than in the individual cost elements. At some airframe weights and speeds the three DAPCA models give similar results. Figure 9 shows that at 300 kn and 5000 lb the lowest estimate is only 56 percent of the highest, and at 300,000 lb they are only about 10 percent apart. At 1500 kn the situation is reversed--a difference of about 10 percent at 5000 lb and about 40 percent at 300,000 lb. DAPCA III is highest at 300 kn, DAPCA I is highest at 1500 kn, and DAPCA II is in between the other two at both speeds.

It would be mere speculation to say that any of the three models should be preferred on the basis of the curves of Fig. 9. Table 2 shows the results of a different kind of comparison. Differences between estimates and actual costs are given for a sample of aircraft produced after 1960. Comparisons are for total cost, including development at 30 and 100 aircraft.

At both 30 and 100 aircraft, DAPCA I overstates the cost of seven out of nine test cases, DAPCAs II and III divide over- and underestimates about evenly. All three models badly overestimate the A-7 and C-141 and badly underestimate the S-3. According to Vought Corporation, the A-7 was a follow-on to the F-8A, which was a follow-on to the F-8U.

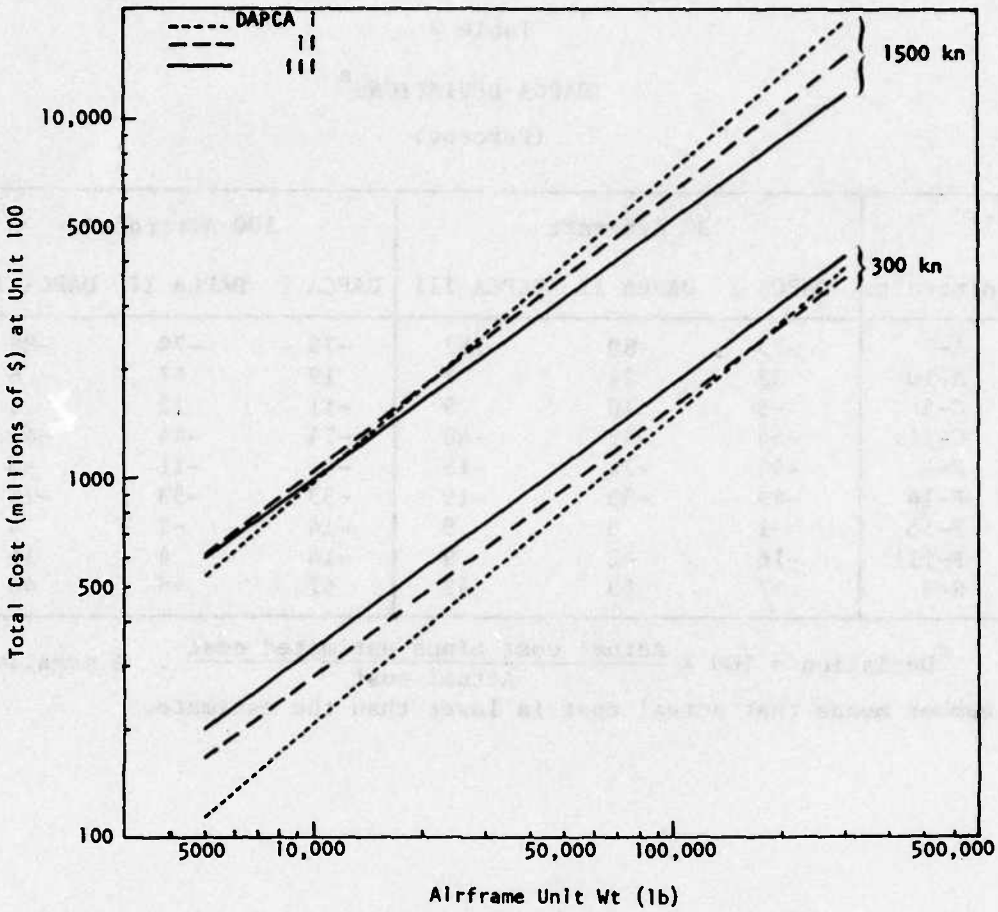

Fig. 9--Comparison of DAPCA total-cost estimates for 100 airframes

Thus, nonrecurring costs were much lower than would have been incurred had the A-7 been an all new airplane. The S-3 is a small, fairly slow aircraft designed mainly to carry electronics equipment. The additional cost incurred in integrating and installing the extensive avionics gear is not reflected in either its weight or its subsonic speed. The high estimates on the C-141 suggest that the DAPCA models should be used very carefully in estimates of the cost of a normal transport aircraft; the surprisingly good estimates by all three on the C-5 (generally conceded to be of above-average cost) reinforce that notion.

Improvement from one model to another is not dramatic, and another sample of aircraft could give different results, but judging from Table 2 we would say that DAPCA III is the most reliable of the three.

Table 2

DAPCA DEVIATIONS[a]

(Percent)

Aircraft	30 Aircraft DAPCA I	30 Aircraft DAPCA II	30 Aircraft DAPCA III	100 Aircraft DAPCA I	100 Aircraft DAPCA II	100 Aircraft DAPCA III
A-7	-75	-80	-187	-79	-79	-85
A-10	32	24	7	19	17	6
C-5	-5	10	9	-11	12	9
C-141	-54	-41	-40	-74	-44	-44
F-4	-44	-24	-18	-31	-11	-5
F-14	-49	-35	-19	-53	-33	-18
F-15	-1	6	9	-14	-2	4
F-111	-16	-2	9	-14	4	14
S-3	57	53	42	57	48	40

[a]Deviation = $100 \times \frac{\text{Actual cost minus estimated cost}}{\text{Actual cost}}$. A negative number means that actual cost is lower than the estimate.

III. PLANNING RESEARCH CORPORATION MODEL

The PRC model is intended for use "in program planning, cost-effectiveness studies, and evaluation of contractor proposals." The last use implies that more detailed information will be required than the Rand model uses, and the PRC model does indeed use inputs not available until a production schedule has been laid out and a contractor chosen. The inputs are of four general types:

<u>Program characteristics</u>

- Quantity of aircraft in each production lot
- Average delivery rate
- Estimate of airframe weight growth factor
- Responsible agency--Air Force or Navy

<u>Aircraft characteristics</u>

- Maximum speed at altitude
- Altitude
- Maximum speed at sea level
- Airframe unit weight
- Aircraft empty weight

<u>Contractor characteristics</u>

- Airframe contractor
- Wage rate, overhead rate, and general and administrative costs (G&A) rate

<u>Time-related characteristic</u>

- Year of first delivery

Not all of the above inputs are required. If an estimate of the airframe weight growth factor, for example, is not available, the model will estimate a factor based on airframe unit weight, production quantity, and the airframe contractor. Similarly, if the contractor is not known, factors are provided. (The contractor adjustment factor--actually a set of discontinuity variables--is intended to allow for differences in contractor accounting practices.)

There are only four cost elements in the PRC model:

Nonrecurring tooling and engineering ($)--includes flight test and manufacturing support of engineering;
Recurring tooling and engineering ($);
Manufacturing labor (hours)--includes quality control;
Manufacturing materials ($).

Note that all estimates are in dollars except for manufacturing labor. That creates a problem for organizations using the model, because the original estimating equations are in 1963 dollars, later updated to 1966. Price-level changes since then have been abnormally high, and adjusting the equations to express 1975 dollars introduces additional uncertainty into the results obtained with the model.*

Table 3 lists the aircraft in the PRC data sample. All began production before 1960, and a number of them date back to the 1940s.

Table 3

PRC DATA SAMPLE

A-3	B-58	F-94	F-4
A-4	RB-66	F-100	F-6
A-5	C-130	F-101	F-8
B-36	KC-135	F-102	FJ-2
B-45	F-80	F-104	FJ-4
B-47	F-84	F-105	
B/TB-50	F-86A	F-106	
B-52	F-86D	F-3	

Range of data

Airframe unit weight (lb): 5072-112,500

Maximum speed (kn): 326-1220

First flight date: 1945-1958

NONRECURRING ENGINEERING AND TOOLING

All nonrecurring costs are included in this category and are

---

*The PRC labor cost index used to adjust basic data to 1963 dollars compares very closely to the Rand index in Campbell, R-568-PR. The materials index used by PRC differs substantially, however. With 1950 as the base year (index number = 100) the PRC number would be 146 and the Rand number 185.

estimated on the basis of the cost per pound of unit one airframe weight. That cost is estimated as a function of S^2 and R, where

$$S = \text{maximum speed at altitude}$$

$$R = \frac{\text{empty weight - airframe unit weight}}{\text{airframe unit weight}} .$$

The ratio R does not vary systematically as airframe unit weight increases; but a plot of cost-per-pound vs weight can be constructed only if one assumes some kind of a trend for R. Since the general trend is for R to decrease as airframe weight increases, a trend line based on observed data was drawn. The slope of that line determines the slope of the curves in Fig. 10. However, it should be kept in mind that R is only a proxy for weight and not a good one. Two aircraft with much the same empty weight, such as the A-3 and F-14 (39,400 vs 36,000), can have

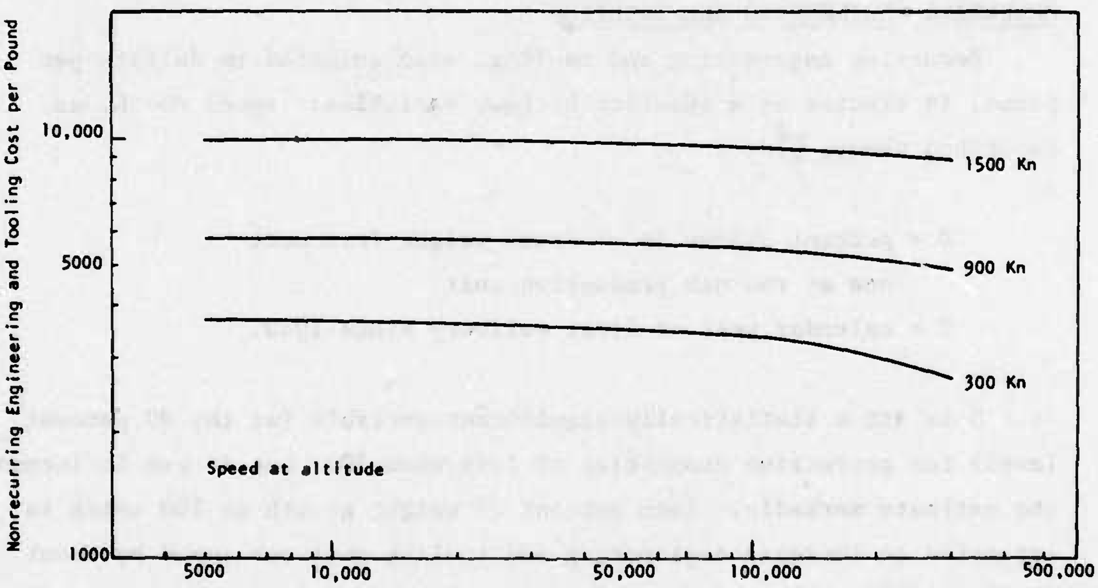

Fig. 10--PRC nonrecurring engineering and tooling cost per pound estimates at three aircraft speeds

very different Rs (.64 vs .38). Thus a small airplane could have a lower R than a large airplane and, assuming equal speeds, would have a lower engineering and tooling cost per pound.

It is clear from Fig. 10 that speed is a much more influential variable than R, and one would have to be careful about using the equation to estimate costs of aircraft faster than those in the sample--i.e., above 1200 kn. Cost per pound is fairly insensitive to changes in weight, which means that total nonrecurring cost is almost a direct linear function of weight.

Nonrecurring costs for a prototype program are recognized to be lower than for a full-scale development program, and that difference is allowed for by the use of a different constant in the estimating equation. The user can also distinguish between Air Force and Navy development programs in the same manner. For a Mach 1 airplane with an R of 0.5, a Navy program would be estimated at 1.67 times the cost of an Air Force program.

RECURRING ENGINEERING AND TOOLING

Recurring engineering and tooling, also esimated in dollars per pound, is treated as a function of four variables: speed and R, as described above, plus:

D = percent change in airframe weight from unit one at the nth production unit.

T = calendar year of first delivery minus 1940.

D is not a statistically significant variable (at the 90 percent level) for production quantities of less than 100, but it can influence the estimate markedly. Each percent of weight growth at 100 units is estimated to increase engineering and tooling cost per pound by about \$1.15 in 1975 dollars; e.g., a 5 percent increase in weight would add \$5.75 to the cost per pound. Where the user is unable to predict weight growth, PRC provides an estimating equation that gives the weight growth factors shown below at 100 aircraft:

Airframe Unit Weight (lb)	Weight Growth Factor (%)
5,000	26.4
25,000	6.4
50,000	3.9
125,000	2.4

Obviously, a 26.4 percent weight growth for a 5000-lb airframe is something to be concerned about, but the other weight-growth factors are less dramatic. The time variable, T, becomes less important each year because the input is in logarithmic form. A change in year from 1955 to 1956 increases engineering and tooling cost per pound by about $1.85. A change from 1975 to 1976 would add only about $.82 (1975 dollars).

The effect of changes in weight (as a proxy for R) and speed is shown in Fig. 11. Note that at 300 kn, cost per pound tails off so rapidly that the cost would be lower for a 300,000-lb airframe than for a 200,000-lb airframe.

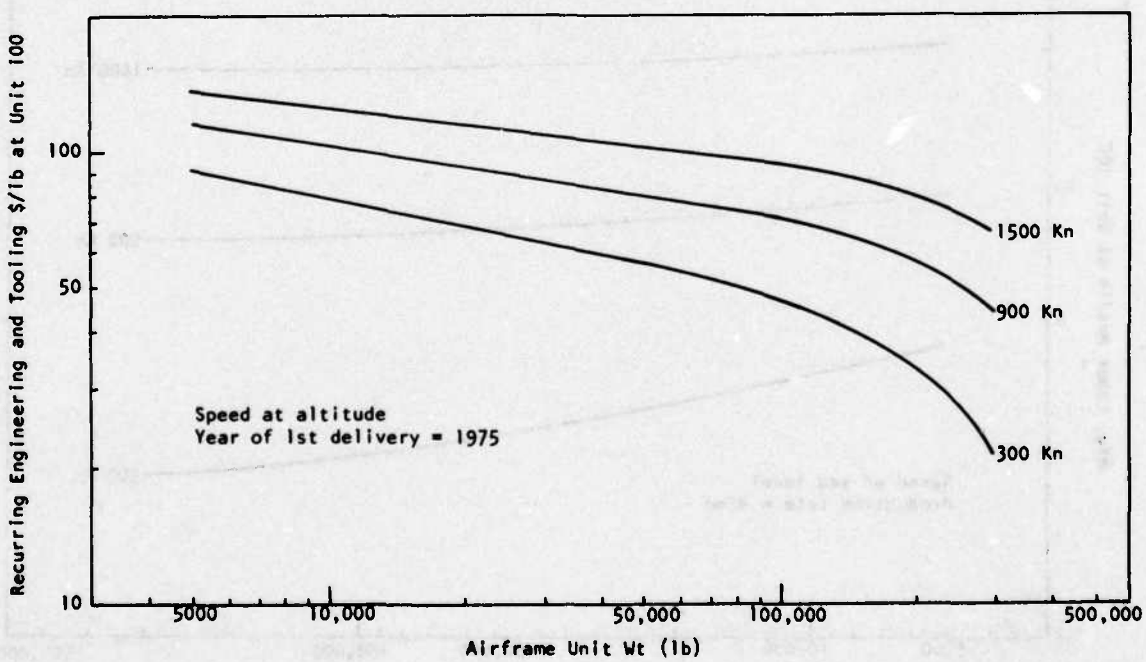

Fig. 11--PRC recurring engineering and tooling cost per pound estimates at three speeds

MANUFACTURING DIRECT LABOR

The equation for estimating manufacturing direct labor manhours per pound of airframe weight has four variables:

$$(\text{Maximum speed at sea level in Mach number})^{2}$$

$$(\text{Delivery rate})^{-.5}$$

$$(\text{Airframe weight})^{-.5}$$

$$(\text{Percent change in airframe weight})^{.5}$$

Speed at sea level, as illustrated by Fig. 12, is by far the most important variable. Delivery rate is important for small production quantities but becomes increasingly less important as quantity increases. Percent change in airframe weight can have a significant effect on manhours under some conditions. A 5 percent increase in weight, for example,

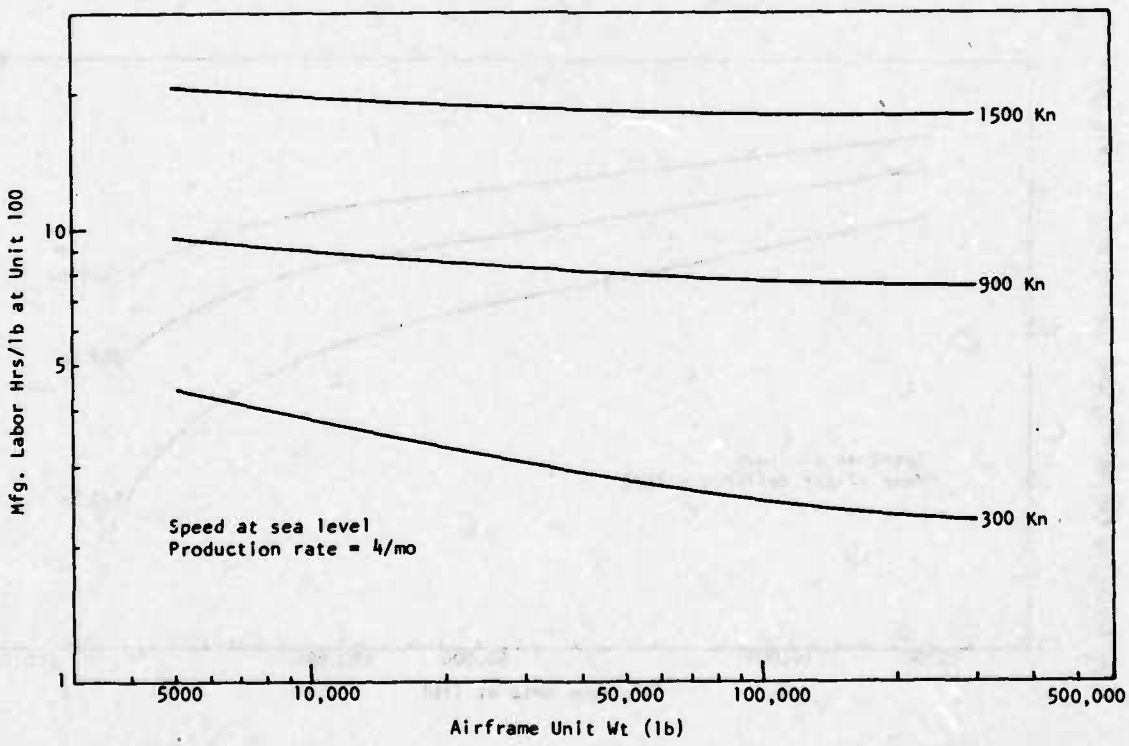

Fig. 12--PRC manufacturing-labor-hours-per-pound estimates at three speeds

would increase manhours per pound by 15 percent for a 30,000-lb Mach 1 airframe.

The most noteworthy feature of the curves in Fig. 12 is their flatness. Ordinarily, one expects a slope of about 85 percent for a manufacturing-hour scaling curve, but the steepest of the curves shown has a slope of 88 percent and the others range from 92 to 98 percent. The effect is to make manufacturing-hour estimates very high for large aircraft.

In addition to the variables, PRC provides a table giving a constant to be used in the estimating equation for some manufacturers. Those constants are in Vol. II of their report and are not generally available. The alternative set, provided in Vol. I, was used in generating the estimates in Fig. 12.

MANUFACTURING MATERIALS

Material costs are estimated in unit cost per pound as a function of aircraft speed, a time factor, airframe unit weight, and delivery rate. Cost per pound varies directly with speed and year of first delivery, and indirectly with weight and delivery rate. Speed is the dominant variable and the only one that was found to be statistically significant at the 90 percent level for all quantities of aircraft examined. The other variables are included because they were considered "logically important in...the airframe manufacturing process."

Figure 13 shows how material cost per pound varies as a function of speed and weight. At higher speeds the curve is fairly flat, which implies that the scaling effect is almost negligible. At lower speeds, however, cost becomes progressively more sensitive to weight, so that from 150,000 lb to 300,000 lb the curve has about a 77 percent slope (in mathematical terms, weight has a coefficient of -.377).

PRC ESTIMATES VS ACTUALS

The PRC model (revised version) was published in 1967 and based on aircraft developed in the 1940s and 1950s. Consequently, only one of the aircraft in the test sample of Table 4, the F-4, was in the PRC data base. Like the DAPCA models, PRC greatly overestimates the cost

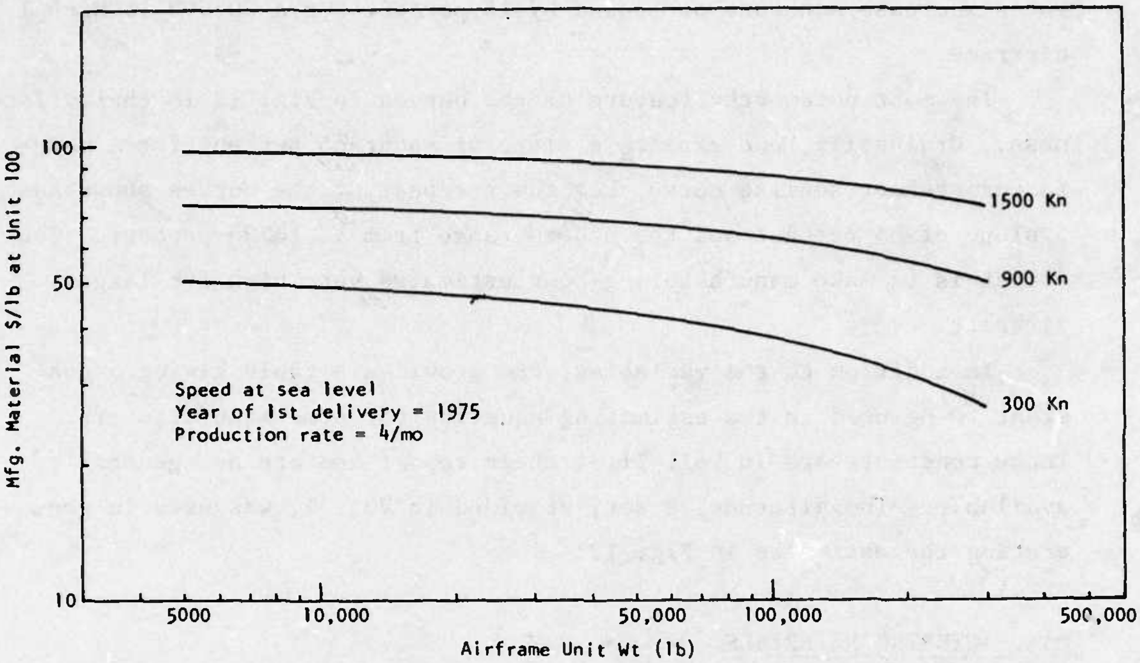

Fig. 13--Manufacturing material cost at three speeds

Table 4

PRC DEVIATIONS

(Percent)

Aircraft	30 Aircraft	100 Aircraft
A-7	-102	-108
A-10	16	8
C-5	-37	-34
C-141	-60	-76
F-4	17	12
F-14	8	-9
F-15	40	25
F-111	31	20
S-3	33	28

of the A-7 and C-141. It also substantially overestimates the C-5, primarily because of the flatness of the manufacturing-labor curves shown in Fig. 12. Manufacturing labor is the most important cost element, and its effect on the estimates is shown by the tendency of the model to underestimate small aircraft and overestimate large aircraft. Part of the effectiveness of the model comes from the distinction between Air Force and Navy programs. Estimates of the F-4, F-14, and S-3 are improved by use of the Navy dummy variable, and that of the A-7 is badly degraded. Like DAPCA, PRC has no provision for follow-on aircraft. All in all, given the PRC data base, the model does a reasonably good job on post-1960 aircraft.

IV. NOAH ASSOCIATES MODEL

J. Watson Noah Associates developed an airframe model for the U.S. Navy (OP96D) in 1973 and in May 1977 published a revised version of that model. We shall refer to them here as JWN I and JWN II. Both differ from the Rand and PRC models in several important respects. First, the only two cost categories are nonrecurring and recurring--defined differently each time. Second, a novel index of technological advance is introduced. And third, a judgmental complexity factor is required.

The convention adopted for separating nonrecurring and recurring costs in JWN I was to construct a cumulative average cost curve including nonrecurring costs, then draw a tangent to that curve at its right-hand extremity, Point B in Fig. 14. The assumption is that as

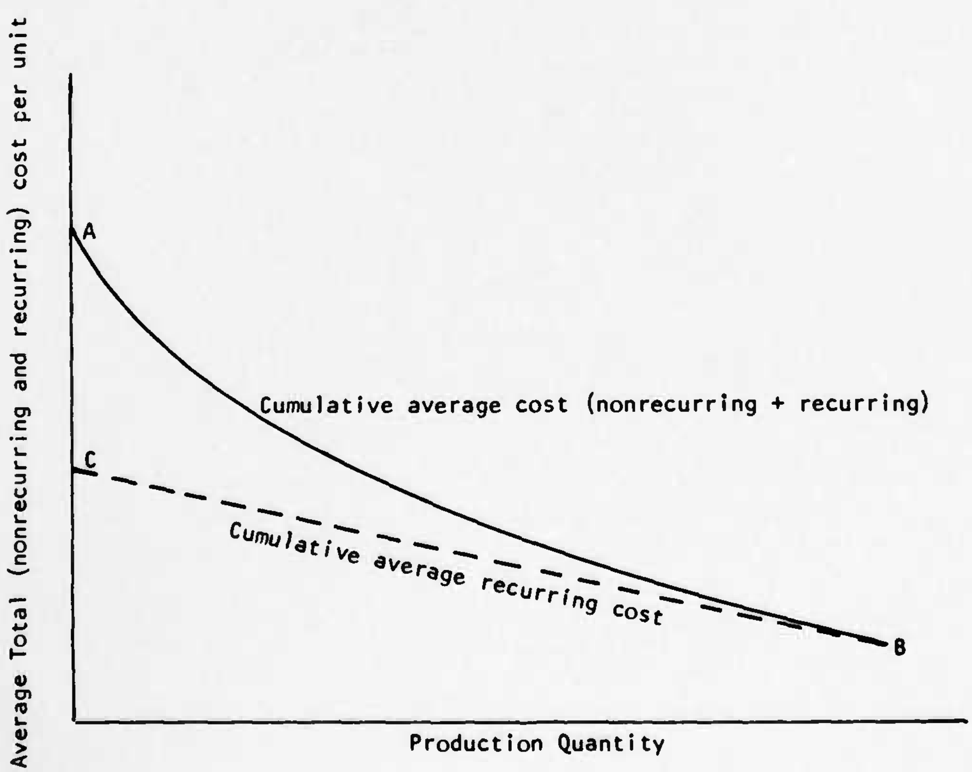

Fig. 14--Determination of nonrecurring cost

nonrecurring costs are spread over larger and larger quantities, Curve AB approaches Curve CB asymptotically, hence the latter is the cumulative average curve excluding nonrecurring costs. Nonrecurring costs are measured on the ordinate as the distance from A to C. The procedure is a reasonable way to ensure consistency in the treatment of nonrecurring costs for a large sample of observations, but the position of Point C on the ordinate is very sensitive to the slope of the line CB. If Point B is at 200 units, a 2 percent difference in slope (78 percent vs 80 percent) means a 15 percent difference in the value of C.

The technology progress index is intended to indicate the variance in cost caused by technological change. Both the Rand and PRC models use calendar time as a proxy for change in some equations, and there is no question but what the continual progression in aircraft technology should be accounted for in some way. The JWN I procedure is based on the hypothesis that a useful proxy can be constructed on the basis of the number of model changes that have occurred since aviation progress began to accelerate during World War I.

A review of technological advances led to the conclusion that the driving factor in most cases was increased fighter performance requirements. Consequently, the cumulative number of different models of fighter airplanes--both U.S. and foreign, and both experimental and production--was chosen as the index of technological progress. From the Nieuport 11 in 1915 to the F-14, 198 model changes were counted. The index numbers assigned to aircraft in the sample are shown in Table 5. They show that certain incongruities result from this method; e.g., the B-47 and C-124 have the same index number, although the former is a much more advanced airplane. Similar problems arise with the use of calendar time.

The judgmental complexity factor mentioned previously is simply a dummy variable based on the notion that any airplane having "a major mission or performance parameter which required significantly new and complex technology" belongs in a separate category of cost. Such aircraft are assigned a variable with a value of one; all other aircraft receive a zero. In the list of aircraft in Table 5, the F-102, F-106, B-58, F-111, and S-3A were considered to be the only ones requiring new

Table 5

TECHNOLOGY PROGRESS INDEX

Aircraft	Index No.	Aircraft	Index No.	Aircraft	Index No.
F-84	161	F-101	185	P-3C	194
F-86	164	F-102	187	T-38	194
F-86D	164	F-104	188	A-7A/B	196
F-3	174	C-133	189	EA-6B	197
B-47	175	KC-135	190	F-111	197
C-124	175	F-105	191	E2-C	198
F-89	175	A-5	193	F-14A	198
A-3	178	B-58	193	S-3A	198
B-66	178	F-106	193		
F-100	179	A-6	194		
F-11F	183	C-141	194		
B-52	184	F-4	194		
A-4	185	OV-1	194		
C-130	185				

Range of data

Airframe unit weight (lb): 5072-112,500

Maximum speed (kn): 309-1370

First flight date: 1947-1974

and complex technology. One might question the inclusion of the F-106 in that category and the exclusion of the B-47, but a more important question is whether one can make the same judgment before development as afterward.

The other variables in the JWN I model are maximum speed, airframe unit weight, and ratio of gross takeoff weight to airframe unit weight. The latter is included because it is said to be high for bomber and cargo aircraft, thus acts to separate them from fighters and attack aircraft. Gross takeoff weight is often rejected as a variable because it has no single value; i.e., it changes from mission to mission. The values used in JWN I are for an aircraft's primary mission.

The preferred equations for nonrecurring and recurring costs (in 1970 dollars) are:

$$C_1 = -5.945 + .00663S + .05138T - 1.4071R + 6.7492\delta$$

$$C_2 = -105.05 + .11557S + 1.2034T - 1.0248A + 97.631\delta$$

where C_1 = nonrecurring cost/lb of airframe unit weight (in thousands)

C_2 = recurring cost/lb of airframe unit weight (cumulative average cost at unit 100)

S = maximum speed at altitude (kn)

T = technical index

R = gross takeoff weight/airframe unit weight

δ = complexity dummy

A = airframe unit weight (in thousands of lb)

In both equations the dominant variable is the complexity dummy, δ. The decision that a new aircraft requires significantly new or complex technology approximately doubles the total cost of 100 aircraft. The technical index, T, is an important variable, but because the number of new models of fighter aircraft is unlikely to change much from year to year, it functions essentially as a constant. The ratio of gross takeoff weight to airframe unit weight, R, can have unexpected effects. In the JWN I sample, the B-58 has a high R, 5.05, which argues for a low nonrecurring cost; and the T-38 has a low R, 2.19, which has the opposite effect. A regression analysis of the JWN I data to determine whether R varies systematically as airframe weight changes indicated no correlation between the two (the R^2 was 0.10). Consequently, it seemed acceptable to use a mean value of 2.935 for R when plotting cost-vs-weight curves.

Figure 15 shows how nonrecurring cost varies as a function of airframe weight and speed when the complexity dummy is zero. Use of a complexity dummy of 1.0 would increase nonrecurring cost per pound as shown below. The need to apply the factor with care is obvious.

Speed (kn)	Cost per pound ($) $\delta = 0$	$\delta = 1$
300	2,190	8,940
600	4,180	10,930
900	6,170	12,920
1,200	8,160	14,910
1,500	10,150	16,900

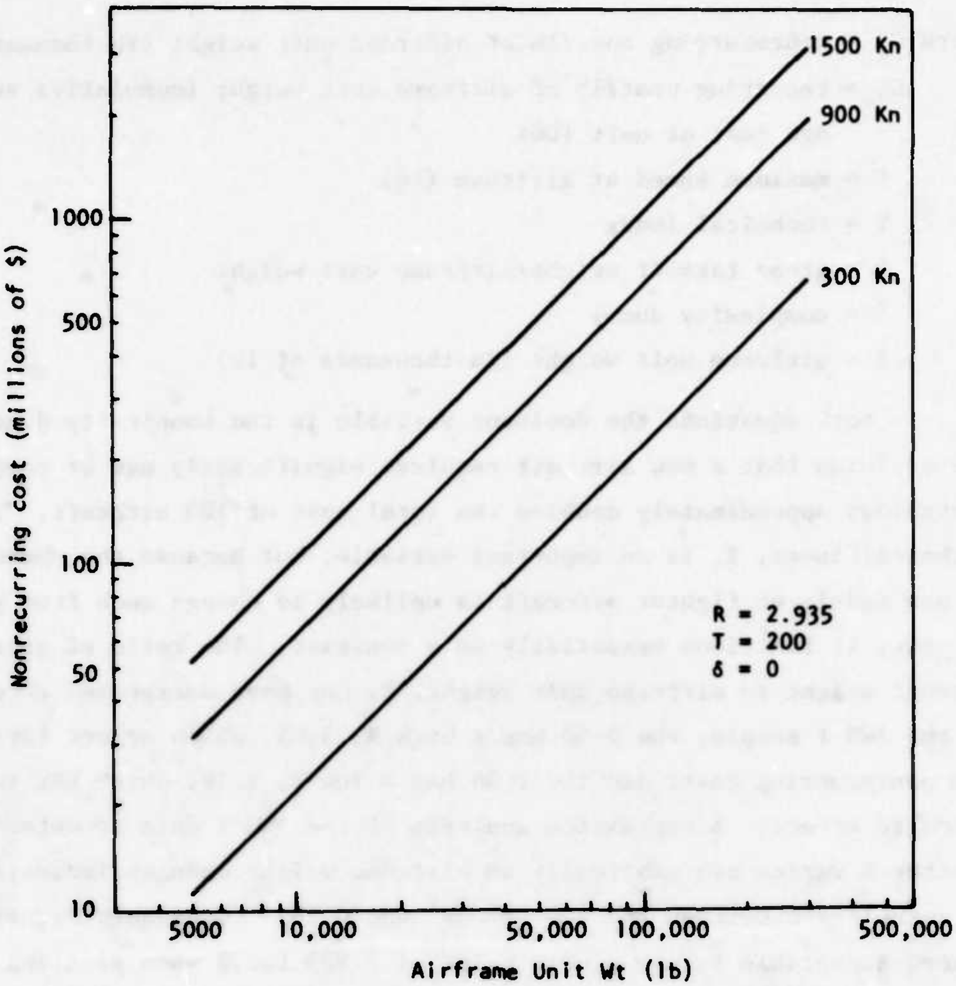

Fig. 15--JWN I nonrecurring cost estimates at three aircraft speeds

In the recurring cost equation when all other variables are held constant, cost increases log-linearly as a function of speed. However, when speed is held constant and airframe unit weight is varied, the recurring cost equation gives results that are not credible. Airframe cost per pound decreases too rapidly as airframe unit weight increases; when cost per pound is converted to cost per airframe, the shape of the curve is found to be parabolic. As shown by Fig. 16, cost peaks at an airframe unit weight that varies with speed and declines thereafter.

The range of airframe unit weights in the data sample is from 5000 lb to 112,000 lb, and estimates within that range may be reasonable

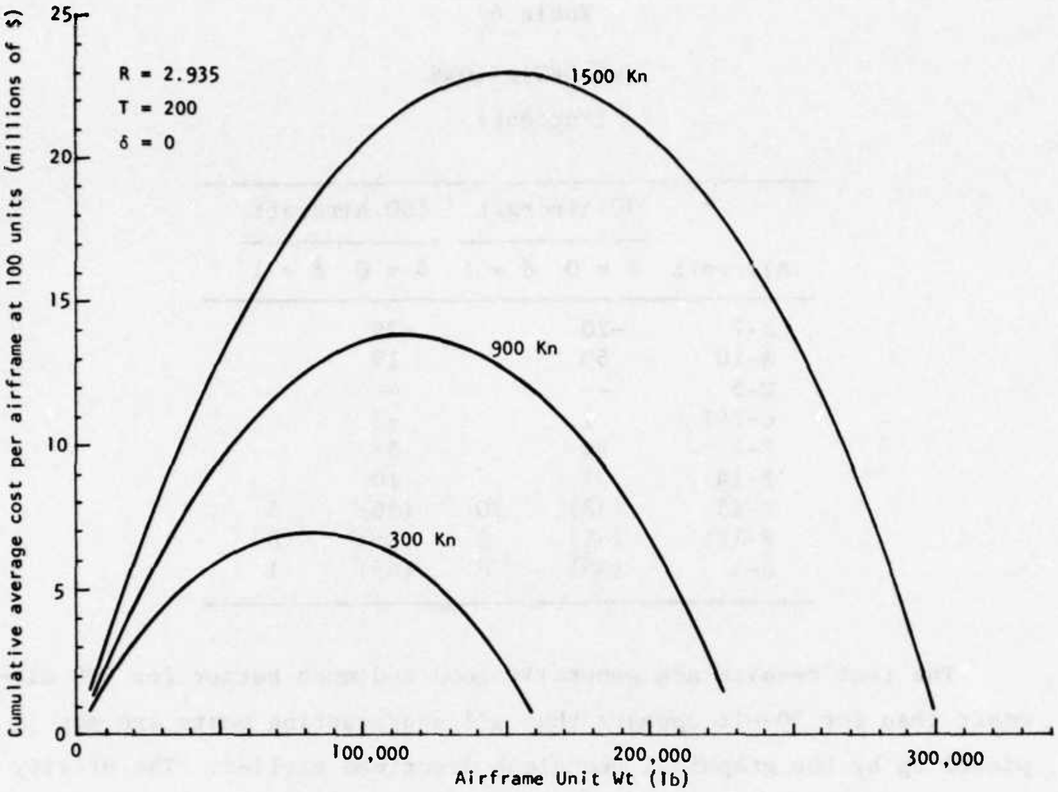

Fig. 16--JWN I estimates of recurring cost per airframe at three aircraft speeds

at some speeds. The curve in Fig. 16 shows clearly, however, that for 300-kn aircraft estimates deteriorate rapidly beginning at about 70,000 lb, assuming that the complexity dummy is equal to zero. Where that dummy is set equal to 1.0, the inflection point in the curve occurs later, but not very much later. Thus it appears that the equation has little value for heavy bombers or cargo aircraft.

JWN ESTIMATES VS ACTUALS

The C-5 cannot be used as a test case for the JWN I model because its recurring cost would be estimated as a negative number when $\delta = 0$ or very close to zero when $\delta = 1$. Also, although the C-141 is included it should be pointed out that the low variances shown in Table 6 are due to overestimates of nonrecurring cost, which balance out underestimates of recurring cost.

Table 6

JWN DEVIATIONS

(Percent)

	30 Aircraft		100 Aircraft	
Aircraft	$\delta = 0$	$\delta = 1$	$\delta = 0$	$\delta = 1$
A-7	-20		-29	
A-10	50		19	
C-5	--		--	
C-141	1		-3	
F-4	36		32	
F-14	21		10	
F-15	(48)	20	(36)	5
F-111	(41)	4	(35)	0
S-3	(55)	8	(45)	1

The test results are generally good and much better for 100 aircraft than for 30--it appears that all nonrecurring costs are not picked up by the graphical technique described earlier. The utility of the complexity factor, δ, is shown for the F-15, F-111, and S-3. Without that factor the model would greatly understate their costs. However, the understatement of A-10 and F-4 costs is the result of specifying a complexity dummy of zero. The importance of choosing correctly and the difficulty of doing so are well-illustrated.

JWN II

The revised JWN model is substantially different from the original and corrects some of the deficiencies noted earlier. Also, the data sample is different. The A-10, C-5, and F-15 were added to the sample, and the A-6, F-11, OV-1, and P-3C were deleted. No reason for the deletion was given. Table 7 shows the model in its entirety.

The first major change is that acquisition costs are called design and production rather than nonrecurring and recurring. Design is defined to include system development, both nonrecurring and recurring, and engineering costs for test airframes. All tooling costs, both nonrecurring and recurring, are included in production.

Table 7

JWN II MODEL

Design Costs:

$$\ln D = -13.013214 + .606684 \ln W + .602425 \ln S - .791948 \ln GW + .877138 \ln F + 1.755809 \ln TI$$

Multiply design cost by: 1.775393 for bomber aircraft

2.185003 for major technology advance

Production Costs:

$$\ln P = -8.246325 + .395885 \ln W + .166260 \ln S + .506351 \ln F$$

Multiply production cost by: .727219 for cargo aircraft

1.199087 for bomber aircraft

1.389824 for major technology advance

where W = airframe unit weight (lb)

S = maximum speed at best altitude (kn)

GW = gross weight (lb)

F = maximum thrust (lb)

TI = technology index

D = design cost in millions of 1975 dollars

P = cumulative average production cost for quantity 100 in 1975 dollars

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A second change is that costs are presented in 1975 instead of 1970 dollars. According to the index shown in the JWN report, aircraft procurement cost increased by a factor of 1.76 over the period 1970-1975. (A direct comparison with DAPCA inflation factors is not possible because Rand computes each functional cost element separately, but it appears that Rand's numbers are about the same as JWN's. To illustrate the uncertainty in index numbers, however, the ASD Cost Escalation Report 110-C would give a factor of 1.44.)*

Historical and Forecasted Aeronautical Cost Indices, Cost Analysis Division, Comptroller, Aeronautical Systems Division, Wright Patterson AFB, April 1976.

A third change is in the equations themselves. The functional form has changed from arithmetic to logarithmic, and several of the independent variables are different. Gross weight has replaced the ratio of gross weight to airframe unit weight, thrust has been added to both equations, and dummy variables are used to distinguish among types of aircraft. The technology index is similar to the one used previously, but only U.S. fighters are included instead of both U.S. and foreign.

The design equation contains three variables that are highly correlated--airframe unit weight, gross weight, and thrust. As can be expected in such cases, spurious results ensue: The gross-weight coefficient has a negative sign, which says that as gross weight increases, design cost decreases. The use of both airframe unit weight and thrust in the production equation is also questionable, because regression results become less stable as the degree of interdependence increases. Extrapolation beyond the sample boundary would be especially hazardous with JWN II.

The high interdependencies noted mean that plots of the kind shown previously--e.g., cost vs weight--cannot be drawn, because a change in one variable cannot be assumed without a change in the others. We can, however, compare the estimates obtained from the revised model with those obtained from the original. As shown by Table 8, estimates for the total cost of 30 aircraft are substantially better for the A-10, F-4, F-14, and F-15; in each case the revised model produces higher estimates. The C-141 estimate is much higher, and for that reason is less accurate. The F-111 is the only aircraft in the list for which JWN II produces a lower estimate. The original model overestimated cost for only one aircraft; the revised model overestimates five. Ignoring changes of 5 percent or less, we note that five estimates are better, two are worse.

For 100 aircraft, the significant fact is that only one variance exceeds 15 percent, an unusual achievement for a parametric model. The critical factor here, as before, is the δ-factor (renamed major technology advance in JWN II). Given the ability to single out major technology advances from only moderate technology advances, estimating can be much more accurate.

Table 8

COMPARISON OF JWN DEVIATIONS

		30 Aircraft		100 Aircraft	
Aircraft	δ	JWN I	JWN II	JWN I	JWN II
A-7	0	-20	-25	29	-25
A-10	0	50	-6	19	9
C-5	1	--	-4	--	-4
C-141	0	1	-33	-3	-15
F-4	0	36	6	32	10
F-14	0	21	2	10	4
F-15	1	40	-17	5	-12
F-111	1	4	14	0	11
S-3	1	8	5	1	6

V. SCIENCE APPLICATIONS INC. MODEL

The SAI model is intended to estimate only the production cost of conceptual transport aircraft. The 17 groups below are designated as cost elements (systems).

Wing	Flight controls	Auxiliary power
Tail	Hydraulic	Furnishings & equipment
Body	Electrical	Instruments
Alighting gear	Pneumatic	Avionics
Nacelle	Air conditioning	Load and handling
Propulsion (less engine)	Anti-icing	

The cost of each system is estimated separately, and the sum of those costs is total aircraft cost exclusive of engines. A cost-estimating relationship was developed for each system using data from the sources indicated in Table 9 plus inputs from studies and industry sources.

Table 9

SAI DATA SOURCES

System	Data Source
Wing	C-141, C-5
Tail	C-5, C-141, KC-135, C-130
Body	KC-135
Alighting gear	C-5, C-141, KC-135, C-130, DC-10, 727, 747
Nacelle	C-5, C-141, KC-135, C-130
Propulsion	C-5, C-141, DC-10
Flight controls	747, L-1011
Hydraulic	Catalog costs
Electrical	Catalog costs
Pneumatic	Subcontractor data
Air conditioning	Subcontractor data
Anti-icing	--
Auxiliary power	Subcontractor data
Furnishings & equipment	DC-9-50, 727/100, 747, DC-10, L-1011, C-130E, C-135B, C-141A, C-133B, C-5A
Instruments	--
Avionics	C-5, C-141, government cost data
Load and handling	--

The procedure could best be described as judgmental, and no statistical parameters were calculated to show the degree of accuracy with which the estimating equation describes the sample observations.

Weight is the only explanatory variable used. The assumption is made that technology will not change in every system utilized by future aircraft; therefore many of the estimating equations will be useful in the future. It is also assumed that the equations will be useful for preliminary estimates of the cost of modifying existing aircraft. All estimates are in 1975 dollars and are for the cumulative average cost of 100 production units.

SAI validated the model by comparing estimated costs with the actual costs of three aircraft: the DC-10-10, C-141A, and F-28. The DC-10 was underestimated by 4 percent and the C-141A was overestimated by 6 percent and the F-28 by 14 percent. The empty weight of the three aircraft above ranged from 29,178 lb for the F-28 to 203,760 lb for the DC-10-10. Within that range and within the speed regime of those aircraft, the model appears to predict with acceptable accuracy. The question we have posed in previous sections, however, is, What happens when the model is used for estimating aircraft outside the limits of the data?

Because of its structure, the SAI model cannot be analyzed at a total-weight level as were the three previous models. The user has to specify a weight for each subsystem, and to do that accurately would require an aircraft design model. We did not have detailed costs on all the subsystems in a representative sample of transport aircraft; consequently, it was not possible to test the model at the subsystem level where, presumably, it would be most useful. Subsystem weights and total observed costs on the C-5, C-130, and KC-135 were available, however, from a PRC Systems Sciences Company study for NASA that was the immediate predecessor to the SAI study.[8] SAI also provided the necessary data on the Boeing 747 to include that aircraft in our test. The estimated cumulative average cost of the 100th aircraft (without engines but including 10 percent profit) is shown along with the observed cost below.* Costs are in millions of 1975 dollars.

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*"Observed" costs for commercial aircraft were actually calculated by SAI from data collected by NASA. They appear to be sufficiently

Aircraft	Observed Cost	SAI Estimate	Deviation (%)
C-130	7.2	7.4	3
KC-135	9.0	8.9	1
C-5	35.0	23.4	33
747-200B	29.5	27.8	6

Three of the estimates are very good, but the C-5 estimate is too far off the mark to be useful. One can point to a number of factors that made the C-5 abnormally expensive--e.g., elaborate avionics, an expensive weight reduction program, an unusual alighting gear, and an inappropriate contractual scheme. Thus the cost should be above that estimated by the model for an aircraft of that class. To understand why the estimate is lower than that for the 747 we must look at the weight statements of those two aircraft. The major differences are in two cost elements: body, and furnishings and equipment.

	Body		Furnishings & Equipment	
Aircraft	Weight (lb)	$/lb	Weight (lb)	$/lb
C-5	115,216	49.3	7,811	67.5
747	68,452	55.8	48,007	76.1

The 747 has a far greater weight of furnishings and equipment, and that group has a higher cost per pound in commercial aircraft than in military. The C-5 body weight is shown as 115,216 lb, but much of that weight is not body structure:

Basic structure	63,017 lb
Secondary structure	5,879 lb
Other miscellaneous weight	46,320 lb

The body weights of the two aircraft are very similar. Other miscellaneous weight includes a separate upper deck troop compartment, an integral cargo loading system, and a visor nose and ramp to permit

accurate for our comparisons but should not be regarded as actual costs. For the C-5A the observed cost at the 100th unit is an extrapolation from the cost of the 81 aircraft produced.

nose loading in addition to tail loading. If those elements were estimated separately instead of being classified as *body*, the estimate would be somewhat improved.

All in all the SAI model appears to do a good job for contemporary transport aircraft with speeds not exceeding Mach .85. As the C-5 example illustrates, however, the user must be alert for unusual weight distributions, because they can seriously bias an estimate.

VI. COMPARISON OF MODEL OUTPUTS

No two of the seven models described above have the same set of cost elements, and where cost elements have the same name they may be defined differently. Total cost, however, is defined in the same way with one exception--an allowance for general and administrative costs (G&A) must be added to PRC estimates. We added 10 percent for G&A, and with that adjustment we believe that Rand, PRC, and JWN models can be compared fairly on a total-cost basis. Since the SAI model estimates production cost only, it is not discussed in this section. We shall compare the estimates of total cost at different quantities and examine how the estimates change as airframe weight and speed are varied. The intent in all the comparisons shown is not to establish that any one model is superior to the others, but rather to show how the outputs differ and to suggest where limitations occur that may make a particular model unsuitable in some situations.

Figure 17 shows a comparison of model outputs, speeds of 300 and 1500 kn, and airframe weights ranging from 5000 to 300,000 lb. At 300 kn the PRC curve is clearly higher than the others at all weights. DAPCA III is highest of the other four at 5000 lb but crosses DAPCA I at about 160,000 lb. JWN I is generally close to the DAPCA curves until it begins to bend over. Although not shown, the curve actually declines beyond 90,000 lb. PRC is still highest at 1500 kn at all weights about 7000 lb. JWN I is lowest at the outset, then is adjacent to DAPCA I until it begins to bend over. DAPCA III is now the lowest of the curves at most weights.

The comparisons in Fig. 17 are all made at 100 units. The same relationship among the curves does not obtain at other quantities because each model uses a different cost-quantity relationship. Figure 18 is illustrative. At 5000 lb, four of the curves are in the same vicinity at 100 units, but the same four diverge widely at 100 units. The three DAPCA curves have essentially the same slope throughout the range and show a greater learning effect. At 50,000 lb, the greatest agreement is at 300 aircraft, and at 300,000 lb it is at 10

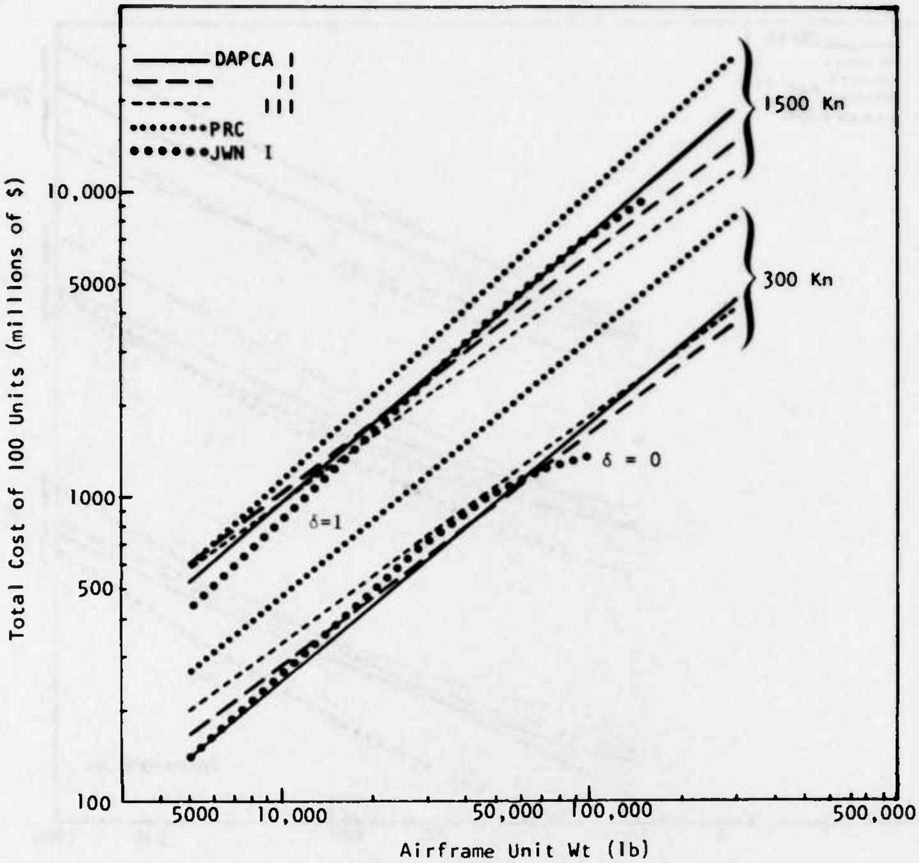

Fig. 17--Total-cost comparison

aircraft. Thus the comparisons among the models shown in Fig. 17 are valid only at 100 units. For other quantities the results could be quite different.

Table 10 recapitulates the deviations shown earlier. The many adjustments to the basic data for differences in quantity and price-level changes plus differences in labor and burden rates among the companies make any kind of a precise comparison impossible. These variances are suggestive of the relative accuracy of the models, but no inferences should be drawn from differences of a few percentage points.

At 30 aircraft, all models overestimate the A-7, which, as explained previously, is to be expected. The JWN models estimate that airplane best because of the procedure they use for separating easy

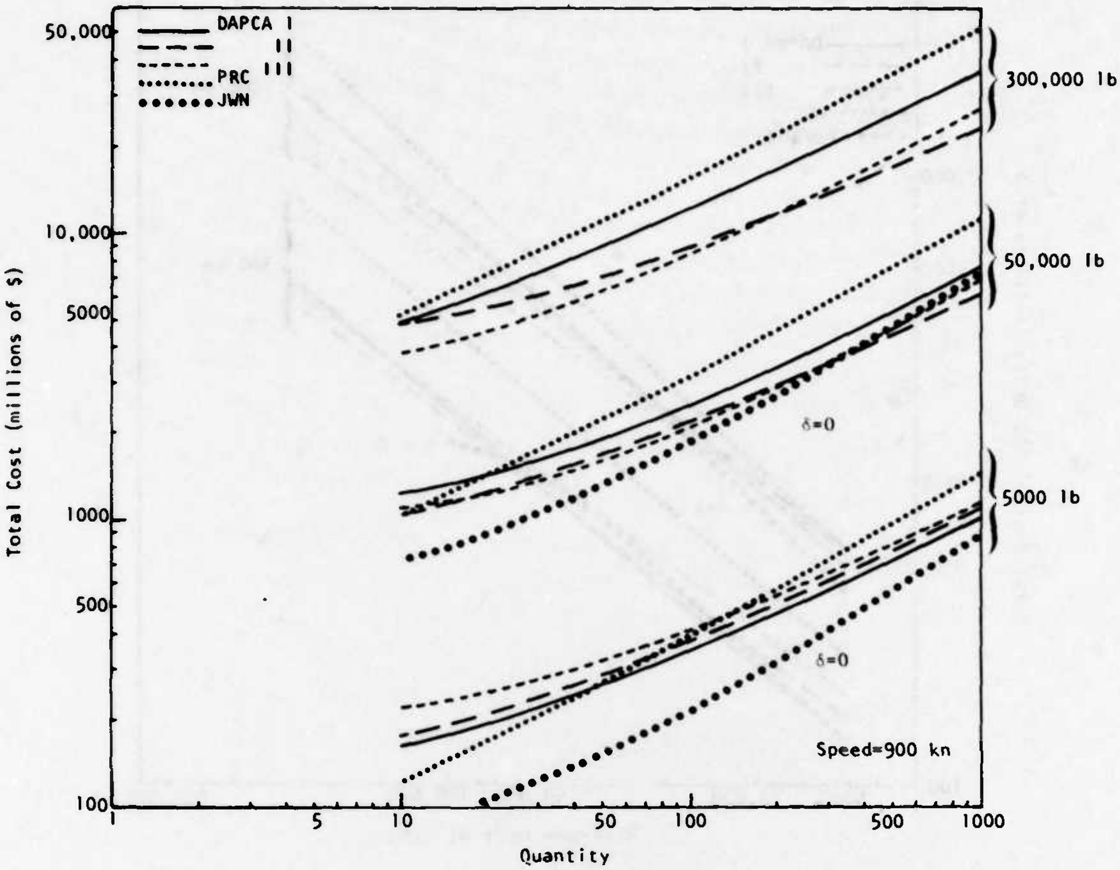

Fig. 18--Effect of quantity on total-cost comparisons

programs from difficult programs. All models but one greatly overestimate the cost of the C-141, and that implies a need to determine whether the data base is appropriate for that type of aircraft. Three models overstate C-5 cost, which is surprising in view of its magnitude; and five models underestimate A-10 cost--nominally, a low-cost program. Only the two JWN models provide useful estimates on the S-3.

DAPCA I is slightly worse at 100 aircraft than at 30, DAPCAs II and III are slightly better and PRC and JWN are decidedly better. Again, all of the models overstate the cost of the A-7 and C-141, and all understate the S-3. DAPCA I overestimates all programs except the A-10 and S-3, JWN I tends to underestimate, and the others show no strong tendency in either direction.

Table 10

DEVIATIONS FOR NINE POST-1960 AIRCRAFT

(Percent)

Aircraft	DAPCA I	DAPCA II	DAPCA III	PRC	JWN I	JWN II
			30 Aircraft			
A-7	-75	-80	-187	-102	-20	-25
A-10	32	24	7	16	50	-6
C-5	-5	10	9	-37	--	-4
C-141	-54	-41	-40	-60	1	-33
F-4	-44	-24	-18	17	36	6
F-14	-49	-35	-19	8	21	2
F-15	-1	6	9	40	20	-17
F-111	-16	-2	9	31	4	14
S-3	57	53	42	33	8	5
			100 Aircraft			
A-7	-79	-79	-85	-108	-29	-25
A-10	19	17	6	8	19	9
C-5	-11	12	9	-34	--	-4
C-141	-74	-44	-44	-76	-3	-15
F-4	-31	-11	-5	12	32	10
F-14	-53	-33	-18	-9	10	4
F-15	-14	-2	4	25	5	-12
F-111	-14	4	14	20	0	11
S-3	57	48	40	28	1	6

If we define a usable estimate for the nine post-1960 comparison aircraft as one with an absolute deviation not exceeding 10 percent, the score would be:

	30 Aircraft	100 Aircraft
DAPCA I	3	0
DAPCA II	3	2
DAPCA III	4	4
PRC	1	2
JWN I	3	5
JWN II	5	5

Another sample could give different results, but from the numbers above one would be inclined to believe that DAPCA III and JWN II provide usable total-cost estimates more consistently than the others. JWN II estimates, of course, are contingent upon the ability to choose the proper complexity factor ahead of time rather than after the fact, and several informal tests at Rand have shown that engineers can disagree about an aircraft program's difficulty. It is obvious, however, that some independent variable, other than weight and speed, is required to distinguish between simple and complex aircraft.

Extrapolation outside the limits of the data is hazardous with any model, but because of interdependence among the variables it would be particularly risky with JWN II. The model does lend credence, however, to what many cost analysts believe--i.e., that total-cost models are more reliable than more detailed models.

VII. CONCLUSIONS

Parametric cost models requiring only a few aircraft characteristics as inputs can provide useful estimates of airframe cost. Unfortunately, they can also produce estimates that may be off-target by over 100 percent, and a user can have little confidence in the output of any model until he has calibrated it against his own experience. Thus the first observation we would make based on this review is that no model should be used uncritically. One should examine the functional form of the equations, the reasonableness of the independent variables, and the consonance of the output with industry experience. We have seen how some cost curves actually become negative, how some variables do not perform the function they are supposed to, and how some cost curves indicate no economies of scale when industry experience indicates the opposite.

We have also seen that models free of estimating anomalies do not consistently produce accurate estimates because the estimates are average values, and not all programs fall in the average category. The immediate remedy is to recognize that fact and make ad hoc adjustments to the estimate to make it more representative of an actual program. Such adjustments are often suspect, however, on the grounds that they support a preconceived opinion of what the answer should be. Consequently, the long-term remedy is to develop better models, and this review suggests possible directions for future work.

The PRC model, for example, has a provision for distinguishing between Air Force and Navy aircraft program costs. In three out of four test cases the estimate was improved appreciably by that feature, so we judge that it might well be incorporated in other models.

The JWN models allow the user to specify whether or not a new aircraft requires "significantly new and complex technology." A correct judgment generally means a good estimate, and an incorrect judgment insures a bad estimate. It would be preferable to have some objective and reliable measure of technological difficulty as a model input, because opinions can differ widely. In several informal experiments at

Rand, estimates were not improved when a degree-of-difficulty index was included as an additional explanatory variable. However, measures of technological change in aircraft turbine engines have been developed and related to cost.* We are inclined to believe that some procedure of that kind is essential if gross errors (e.g., the DAPCA estimates on the A-7 and S-3) are to be avoided. If an objective procedure cannot be developed, comprehensive guidelines for making a subjective assessment may suffice.

JWN II also used dummy variables to distinguish among types of aircraft: cargo, bomber, and fighter/attack/patrol. That device offers the benefits of a stratified sample without a reduction in sample size. DAPCA III found such dummy variables useful in only one cost element--flight test--but a more careful distinction among types of aircraft might be productive.

It has been suggested that a major determinant of development cost is contractor experience; i.e., one would expect a contractor with recent experience on a particular type of aircraft to be more efficient than a contractor without that experience. Similarly, one would expect a derivative aircraft to require fewer engineering hours than an all-new aircraft, as in the case of the A-7. The problem in both cases is to define such terms as "recent experience" and "derivative" in such a way that they can be applied consistently. In an experiment at Rand we found widely varying opinions on what constitutes a derivative airplane. Still, such contractor-related variables should be investigated.

For reasons set forth in the Introduction, we do not believe a model should go too far in the direction of describing a specific program rather than a generic one. A variable found in several of the models reviewed, production or delivery rate, seems inappropriate for early planning estimates because early predictions of rate are generally overstated. In addition, judging by differences among PRC, DAPCA I, and DAPCA II, the effect of production rate on cost is not well understood.

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*See, for example, J. R. Nelson and F. S. Timson, *Relating Technology to Acquisition Costs: Aircraft Turbine Engines*, The Rand Corporation, R-1288-PR, March 1974.

Use of production rate as a variable in those models did not appear to improve estimates in the test cases and in some cases made them worse.

In conclusion, airframe cost models of the type reviewed here can be useful, but they are intended as planning tools and that limitation should be recognized. The newer models appear to do a better job than the earlier ones, primarily, we believe, because of better and more recent data. The next generation should be even better. We are not yet ready to speak of a DAPCA IV, but in a dynamic field where engineering, materials, and production methods are changing continuously, airframe models must reflect those changes. New models will be developed, and we hope that some of the lessons learned in this exercise will contribute to their improvement.

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